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NONLINEAR ACOUSTIC MEASUREMENTS AHEAD OF A NOTCH DURING FATIGUE (POSTPRINT)

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Interim Report

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ABSTRACT. This paper presents measurements of relative nonlinear acoustic parameter (β_{rel}), ahead of a notch in Al 7075-T651 dog bone samples, subjected to fatigue. It is compared with crack growth measurements on the same samples. Measurements performed on two samples subjected to identical fatigue conditions that failed at vastly different number of fatigue cycles are described. The β_{rel} measurement for both samples as a function of fatigue cycles was fit a Boltzmann curve. The role of changing β_{rel} ahead of a notch is explored as a possible approach for remain life evaluation.

Keywords: Nonlinear Acoustics, Fatigue, β Parameter, Stress Raiser
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INTRODUCTION

Measurement of the nonlinear acoustic parameter, β, has been shown to be a potential method for detecting fatigue damage in metallic materials [1]. Many research groups have shown that β increases by several hundred percent as fatigue damage accumulates [2-14]. In a large majority of these measurements, dogbone samples with uniform gauge section (flat or cylindrical) have been used [6-15]. Damage accumulates uniformly in these samples when subjected to fatigue, and the final fracture can occur anywhere in the gauge section. While this is effective in producing uniform damage, detection of the most probable location of failure requires β measurements at multiple locations or a complete scan of the gauge section. Currently there is very limited progress in the development of scanning systems for β measurements and most often researchers perform measurements at predetermined locations along the gauge section. Consequently, measurements at multiple locations are very time consuming. It is well known [16] from fracture mechanics that the cracks initiate at locations where stress is high (stress raiser). Samples designed with stress raisers are often used in fatigue life prediction studies in fracture mechanics. Nonlinear acoustic parameter measurements near a stress raiser provide a unique opportunity to compare with standard crack growth studies. This paper presents β measurements just ahead of a stress raiser, in the form of a semi-circular notch, in the gauge section of flat dogbone samples. This paper describes the details of the design

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and development of instrumentation and a sample fixture to measure the nonlinear acoustic parameter, β, by detecting and measuring second harmonic acoustic signals generated by the sample while in a fatigue machine. Results of preliminary measurements on Al 7075-T651 samples subjected to fatigue are presented.

NONLINEAR ACOUSTIC BACKGROUND

It is well known that a sinusoidal monochromatic acoustic wave propagating in a material will be distorted due to nonlinear acoustic interactions in the material. The distorted acoustic signal can be considered as a combination of fundamental, second, third, fourth etc., harmonic signals. The amplitude of higher harmonics decreases inversely with the harmonic number. The most often observed harmonic signal is the second harmonic generated by the sample. The propagation of an acoustic wave in a nonlinear material can be described with (1).

$$\rho \frac{\partial^2 u}{\partial t^2} = c_l^2 \left[1 - \beta\left(\frac{\partial u}{\partial x}\right)\right] \frac{\partial^2 u}{\partial x^2} \tag{1}$$

In (1) β is the nonlinear acoustic parameter and c is the longitudinal wave velocity. A perturbation solution of (1) leads to definition of β based the absolute amplitude of the fundamental and second order harmonic signal given by (2).

$$\beta = 3 + \frac{C_{111}}{C_{11}} = \left(\frac{8}{ak^2}\right)\left(\frac{A_2}{A_1^2}\right) \tag{2}$$

In (2) C_{11} and C_{111} are the second and third order elastic constants respectively, and *a* is a characteristic dimension of the test specimen. A_1 (m) is the fundamental signal amplitude at a frequency of f_o and A_2 (m) is the second harmonic signal amplitude at frequency of $2f_o$, k is the wave vector (3), and c_l is the longitudinal speed of sound in the material.

$$k = \frac{2\pi f_o}{c_l} \tag{3}$$

The nonlinear acoustic parameter, β as defined in (2) is an absolute dimensionless quantity. In a large majority of measurements, A_1 and A_2 are measured as voltages and hence the nonlinear acoustic parameter has dimension of V^{-1}. There are methods to convert the voltages into absolute displacement that are quite involved. When experiments involve comparative measurements of different states of the same sample, it may be sufficient to have a relative (β_{rel}) measurement. In current experiments we are interested in β_{rel} measurements and hence no attempt was made to convert the voltages into displacement.

MEASUREMENT SYSTEM AND MATERIALS

Measurement Instrumentation

Instruments and approaches used by several groups [5, 6, and 8] to measure β were incorporated to develop a customized system. Figure 1 shows the main components of the system. A 10 MHz (f_o) tone burst of frequency, generated by a function generator (Agilent

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Model 33250A Waveform Generator) is amplified by a high power amplifier (TOMCO Model BT00250 RF Power Amplifier), and passed through a high power narrow band filter. The amplified tone-burst excites a 10 MHz piezo-electric transducer (Panametrics Model V129-RM) bonded to a sample. A 20 MHz transducer (Panametrics Model V116-RM) detects the acoustic signal through the sample. The detected signal is split into two parts. The first part is fed directly into one channel of a digital oscilloscope (LeCroy Wave RUNNER Model44Xi-A). This signal is the attenuated signal through the sample that has the same 10 MHz frequency and its amplitude is A_1. The second part of the signal is filtered using two narrow band (20 MHz) filters and amplified by a custom designed low noise, narrow band amplifier (Miteq). The 20 MHz second harmonic signal (A_2) generated by the sample is fed into another channel of the oscilloscope. The amplitudes of function generator input signal, A_1, and A_2 were acquired and used for analysis using a computer. Custom control and collection software was written in LabVIEW for use with the system. To determine the relative β_{rel} the tone burst amplitude was sequentially increased from 100 to 200 mV_{pp} by 5 mV. The amplitudes of A_1 and A_2 were recorded at each input step and the β_{rel} was determined from the plot of A_2 v/s A_1^2.

Sample and Fixture Design

Measurement of β_{rel} on a flat and parallel sample can be performed without much difficulty. These experimental measurements were performed on flat dog bone samples with a notch, while the sample is held in the grips of a fatigue machine. Another requirement was for measurements to be performed without removing the sample from the grips of the fatigue machine. These requirements posed several challenges most notably holding the transducer pairs in position just ahead of the notch and consistently making measurements at the same location.

Nonlinear acoustic parameter measurements are most often an average over a volume of the sample. In a dog bone sample with a notch, most of the damage accumulation is expected to occur in a small region just ahead of the notch. Although significant changes in β_{rel} may occur near the notch, the measurements are averaged over the thickness of the specimen. The averaged value may be small and hence the sensitivity needs to be increased. For this purpose β_{rel} measurements, were also performed at two fixed locations on either side of the notch. Since the damage accumulation is localized, the measurements in the adjacent locations can be used as reference in the analysis. This approach added further complexity and challenge to the development of fixture and experimental measurements.

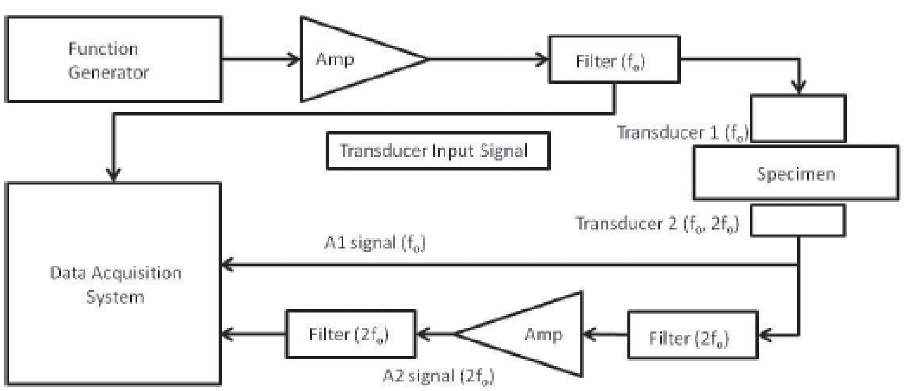

FIGURE 1. Schematic of the relative nonlinear acoustic parameter measurement system.

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Flat dog bone samples of Al 7075-T651 were designed with two notches that act as stress raisers. The samples were 145 mm in length with a 9.1 mm wide and 6.3 mm thick gauge section. Each notch has a diameter of 2 mm with a center offset 1 mm from the edge of the specimen giving a total of 7.1 mm between the notch tips. A close up of the central section of the sample is shown Fig. 2a. A fixture (Fig. 2c) to hold and align three pairs of transducers parallel to each other on either side of to the sample was designed. A small protrusion, with the same diameter as the notch (highlighted in Fig. 2c), on the bottom of the fixture was designed to snugly fit into the notch of the test specimen. This protrusion helps to quickly align the transducers on the specimen, and to make measurements consistently at the same location every time.

Experimental Measurement Details

The specimens were cyclically loaded at 30 Hz with a sine wave input at a maximum stress of 350 MPa with an R-value of 0.5 until failure. Nonlinear acoustic measurements were performed using through transmission with two sets of three transducers placed on either side of the specimen as shown in Fig. 2b. All transducers have a nominal element diameter of 3.175 mm and were centered on the sample. A very thin layer of honey was used to couple the transducers to the sample. To ensure that the A_1 and A_2 signals have sinusoidal features without distortion, the fundamental frequency, f_o, was tuned to 9.52 MHz. β_{rel} measurements were acquired periodically by stopping the fatigue testing. At each interruption, measurements were performed at all three locations (A, B, and C) on the sample. At each location, three β_{rel} measurements were acquired and averaged. The instrumental conditions were kept the same for all the measurements and the data was acquired while the specimen was in the grips of the fatigue machine (MTS). At each interruption the fixture was removed, the area of the notch was cleaned with alcohol, and acetate replicas of both notches were acquired for crack growth studies for comparison with β_{rel} measurements.

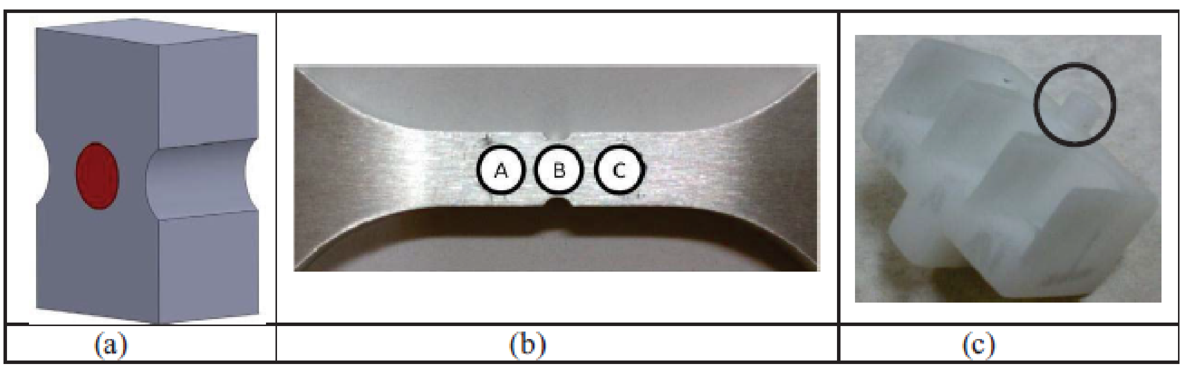

FIGURE 2. a) 3D representation of the central gauge section showing the notches on either side. The small red circle is the area where the transducer face element would rest, b) Transducer measurement locations, c) one half of the custom test fixture used to hold and align the transducers.

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RESULTS AND DISCUSSION

The data collected at three locations was analyzed to determine β_{rel} from the region just ahead of the notch (Location B). The data from locations A and C was used as reference and a new relative nonlinear acoustic parameter for location B was determined using (4).

$$\beta_{rel}^{B} = \beta_{Brel} - \left(\frac{\beta_{Arel} - \beta_{Crel}}{2}\right) \tag{4}$$

β_{rel}^{B} was normalized to the maximum measured value for the specimen. Figure 3 shows the variation of β_{rel}^{B} in a sample that failed at approximately 54000 cycles, while Fig. 4 shows the variation in a sample that failed at 32000 cycles. The figures also show the lengths of the longest cracks measured using acetate replicas growing from both notches. The figures show that as the number of fatigue cycles increase the β_{rel}^{B} also increase. The rate of increase for the two samples is different. The entire curve can be fit with a Boltzmann curve (5).

$$\beta_{rel}^{B} = (\beta_{rel}^{B})max + \frac{(\beta_{rel}^{B})min - (\beta_{rel}^{B})min}{1 + e^{\frac{(N-N_o)}{dN}}} \tag{5}$$

$(\beta_{rel}^{B})_{max}$ and $(\beta_{rel}^{B})_{min}$ are the minimum and maximum asymptotic values, N_o is the point of maximum growth, N is the current fatigue cycle count, and dN is a growth rate. Since dN is in the denominator the larger the value the slower the growth. This is the most crucial factor in determining the time to failure. The best fitting parameters for the two samples examined are shown in Table 1. The major difference between the two samples as determined from the curve fit is the growth rate. The growth rate in specimen 1, which failed at 54,000 cycles, is about an order of magnitude larger than in specimen 2, which failed at 32,000 cycles. There are few severe outliers in the β_{rel}^{B} data for both samples. In spite of the outliers the curve fits seems reasonable. It is suspected that the outliers might be result of inconsistent coupling and improper surface contact between sample and transducers. These inconsistencies appear to arise from having to remove and attach the fixture periodically to make measurements. In addition, the surface condition of the specimen is a critical factor, as repeated removal and replacement of the test fixture cause small scratches to form.

The crack growth data in both the samples shows a steady increase as the fatigue cycles increase, eventually reaching a maximum surface length of approximately 580 μm and 480 μm for the left and right notches respectively for specimen 1, and 600 μm and 500 μm for specimen 2. The measured crack lengths are parallel to the surface of the notch.

TABLE 1. Details of the Boltzmann Fits for each specimen.

	Specimen 1	Specimen 2
$(\beta_{rel}^{B})_{max}$	0.147	0.173
$(\beta_{rel}^{B})_{min}$	0.936	0.820
N_o	24324	18114
dN	6069	701
Cycles to Failure	~54,000	~32,000

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Assuming that the cracks have half penny geometry, the maximum depth the cracks penetrate the sample, just before fracture, is roughly 300 μm. Even at this maximum depth, the cracks do not penetrate far enough into the material to interact with the ultrasonic beam. This indicates that the majority of the change in β_{rel}^{B} is due to changes in the microstructure of the sample in the region between the two notches. In effect, the nonlinear acoustic parameter is sensitive to the microstructure changes occurring ahead of the notch/crack and may indicate that fatigue damage may have occurred in a region before micro cracking could be initiated. It is well known from previous studies [6-15] on uniform dog bone samples, that nonlinear acoustic parameter increases even before the cracking occurs. This paper indicates that even in the presence of stress raisers, the nonlinear acoustic parameter changes can be observed at least 2 mm away from a stress raiser when the sample is subjected to fatigue damage.

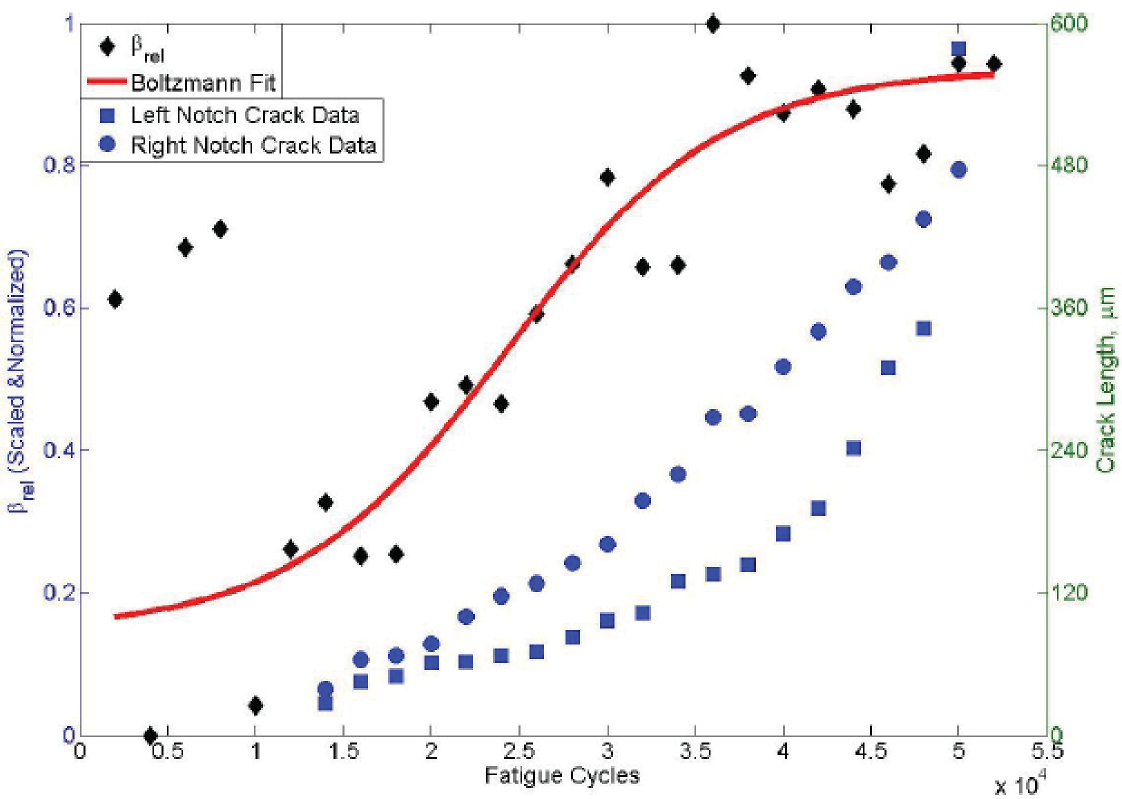

FIGURE 3. Plot of scaled and normalized β data, Boltzmann fit, and crack length data for specimen 1.

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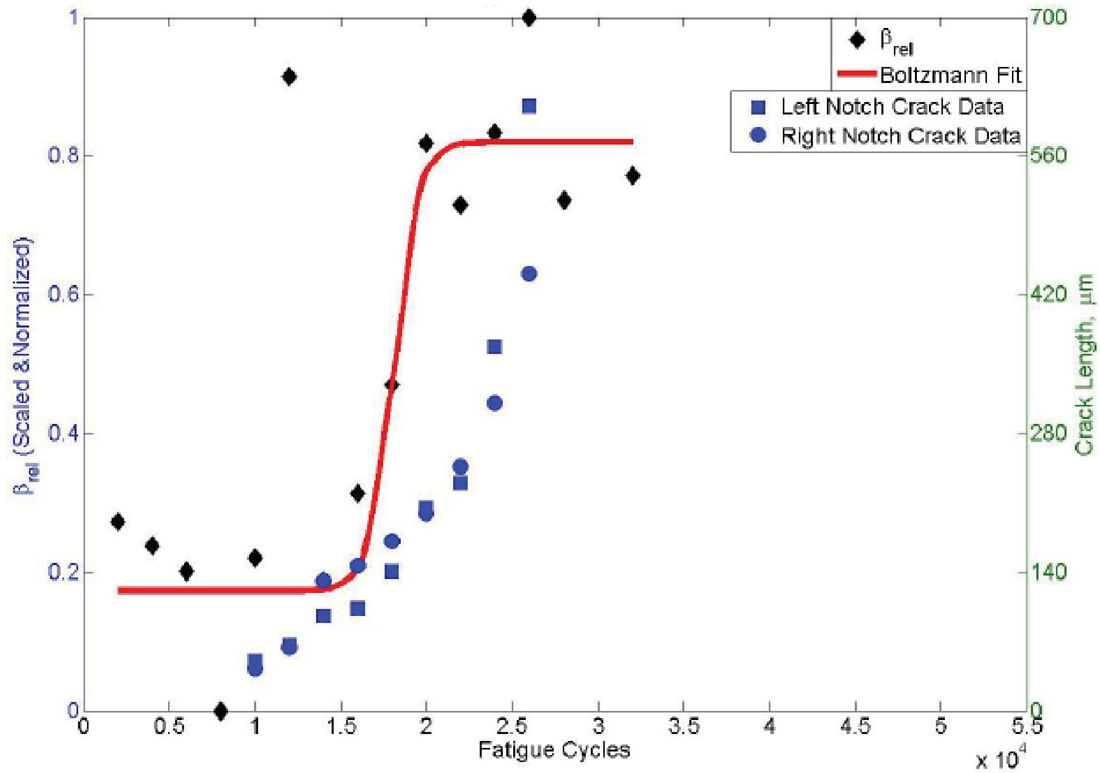

FIGURE 4. Plot of scaled and normalized β data, Boltzmann fit, and crack length data for specimen 2.

SUMMARY

Relative nonlinear acoustic parameter measurements, ahead of a notch in a flat dog bone samples of Al 7075-T651, were performed periodically while subjecting the sample to cyclic loading. Measurements on two samples subjected to same fatigue conditions were performed. Specimen 1 failed at approximately 54000 cycles while specimen 2 failed at 32,000 cycles. The experimental data from both samples was fit to a Boltzmann curve. In spite of a few outliers, the data fit was found to be reasonable. The crack growth (parallel to the notch surface) in the notch region was measured using acetate replicas and compared with the relative nonlinear acoustic parameter. It was found that that the majority of the changes in the nonlinear acoustic parameter occur well before the cracks reach a depth where they begin to interact with the ultrasonic beam. This suggests that the majority of the increase in β^{B}_{rel} was due to changes in the microstructure of the material between the notches. The measurements of relative nonlinear acoustic parameter presented in the paper shows that changes nonlinear acoustic parameter can be observed at least 1-3 mm away from a stress raiser (notch) when the sample is subjected to fatigue.

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